

A Framework for Optimizing the Design of Injection Molds with Conformal Cooling for Additive Manufacturing

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Abstract

This work presents a framework for optimizing additive manufacturing of plastic injection molds. The proposed system consists of three modules, namely process and material modeling, multi-scale topology optimization, and experimental testing, calibration and validation. Advanced numerical simulation is implemented for a typical die with conformal cooling channels to predict cycle time, part quality and tooling life. A multi-scale thermo-mechanical topology optimization algorithm is being developed to minimize the die weight and enhance its thermal performance. The technique is implemented for simple shapes for validation before it is applied to dies with conformal cooling in future work. Finally, material modeling using simulation as well as design of experiments is underway for obtaining the material properties and their variations.

Keywords: Injection Molding, Topology Optimization, Additive Manufacturing

1 Introduction

Plastic injection molding is a versatile process that uses heat and pressure to convert thermoplastic and thermosetting materials into a variety of complex shapes with high-quality surface finish and dimensional precision (Kauffer, 2011). The design of tooling for plastic injection is considered critically important for the quality of the product and the economy of the entire injection molding process.

Presently, the design features of injection tooling are limited by the manufacturing methods used to fabricate them, particularly in terms of geometry freedom and the ability to include innovative features. Current design and manufacturing practices often lead to sub-optimal solutions for an industry in need of increasingly shorter lead times and lower costs as well as higher injection performance and

product quality. Additive manufacturing holds the promise of cleaner and environmentally friendlier operation, and allows complex injection tooling production. However, local mold manufacturers have reported directly to our group that due to high initial investment, specialized maintenance, and substantial material cost, metal Additive Manufacturing (AM) is about 50% more expensive than traditional machining. The current high cost of metal AM constitutes the main obstacle to its implementation in the injection tooling industry. Fortunately, novel simulation-based design optimization methods (e.g., multi-scale thermo-mechanical topology optimization) allow the generation of lightweight, high-performance, and cost-effective injection tooling through additive manufacturing.

In this research, we propose a framework for optimizing the design of dies with conformal cooling for additive manufacturing (Fig. 1). We have started the research on three components in this framework, namely, numerical thermal finite element (FE) modeling, thermal-mechanical topology optimization at macroscale level, and material characterization. Particularly, a literature review for additive manufacturing principles is carried out at first. Secondly a CAD model is established based on these principles and then a transient thermal Finite Element Analysis (FEA) is performed. The resulting is used as input to the thermal-mechanical topology optimization. This step aims to find the optimum materials distribution between the cavity and the coolants. Finally, a material characterization procedure is proposed to validate the structure of the optimum layout.

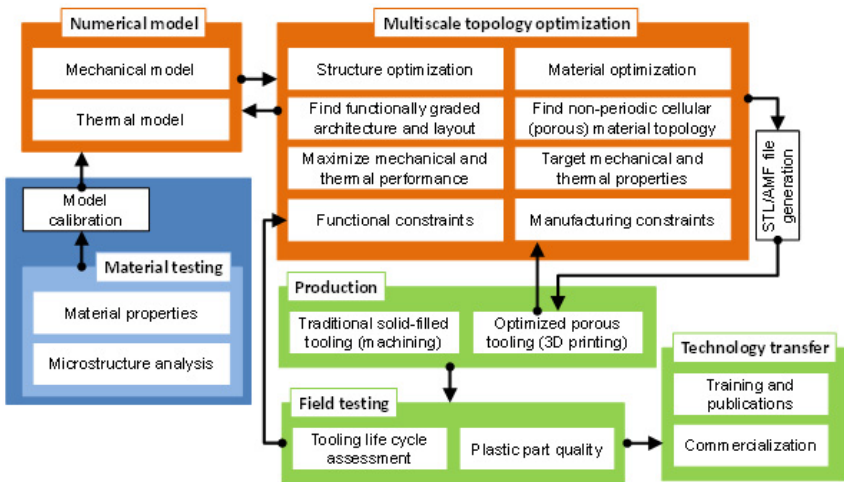


Fig. 1: Framework for optimizing the design of dies with conformal cooling for additive manufacturing

2 Background

Additive Manufacturing. Additive Manufacturing (AM) has already revolutionized the manufacturing technology in producing real functional parts including metals, ceramics and polymers(Mognol et al., 2012). The AM technologies have proven their potential to create injection molds with conformal cooling channels(Petrovic et al., 2011). The quality of the AM part has its own specific characteristics no matter what type of AM technology has been used. Tools with conformal cooling channels manufactured by this process have improved part quality and production rate as compared with conventional production tools.

Even though it provides a lot of benefits and potentials in producing complex structures, the complete establishment of AM process at industrial level is not accomplished yet (Hague et al., 2003). Also the classic design approach for traditionally machined dies restricts AM application. A systemat-

ic approach based on a comprehensive set of design rules to take advantage of the geometric freedom of Additive Manufacturing is needed.

Conformal cooling simulation. The use of cooling channels conformal to the molding cavity improves the control of mold temperature and part dimensions. This has been reported by a group at MIT in the 1990's (Sachs et al., 2000). Since then, different simulation packages have been used to analyze the tool and channel designs for conformal cooling. Dimla *et al.* used Moldflow analysis in I-DEASTM to find the best position of the runner (Dimla et al., 2005). Saifullah and Masood analyzed part cooling times using ANSYS thermal analysis software in 2007 (Saifullah and Masood, 2007). In 2009, this same group used MPI simulation software for part analysis and compared results for conventional and square section conformal cooling channels, concluding that conformal channels render 35% less cooling time than conventional ones (Saifullah et al., 2009).

Gloinn et al. from Ireland performed FEA analysis to determine mold temperature using ABS polymer as molten material and water at 20°C as cooling fluid (Gloinn et al., 2007). Another study was conducted using Moldflow Plastic Insight 3.1 to investigate the thermal effects of cooling channel design on injection molding in 2007 by Au and Yu (Au and Yu, 2007). They proposed a novel scaffold for the design of uniform conformal cooling. Using the same simulation software, Wang et al. verified the advantages of a cooling circuit and modeling part temperature (Wang et al., 2011). A thermal-structural FEA analysis coupling results from ANSYS Workbench and Autodesk Moldflow Advisor in terms of temperature and stress distribution was reported by Saifullah et al (Saifullah et al., 2012). (M. and G., 2012) focused on the selection of an injection molding tool that would provide a high production rate of products without aggravation of quality and thus stated SolidWorks® as a possible software decision. Omar et al. (Mohamed et al., 2013) investigated volumetric shrinkage, warp age and sink marks on parts with conventional, conformal and cooling channel baffles using Autodesk Moldflow Insight (AMI) software. A comparative studies involving conventional, series, parallel and additive parallel cooling channels was reported by Khan *et al.* using AMI software (Khan et al., 2014).

Topology optimization. Topology optimization is a design approach that finds the “best possible” or “optimal” structure by distributing material without any preconceived shape (Bendsoe and Kikuchi, 1988). This unique design approach is recognized as a promising method for obtaining heterogeneous structures with extreme properties (Torquato, 2010). The current framework involves establishing a computational tooling design method through thermo-mechanical multi-scale topology optimization, which will be conducted in four steps, namely: (1) mechanical modeling, (2) thermal modeling, (3) multi-scale mechanical design optimization, and (4) multi-scale thermo-mechanical design optimization.

A multi-scale thermal-mechanical topology optimization approach leads to the generation of lightweight, high performance and cost effective injection tooling through additive manufacturing. The proposed automated design strategy to find optimal material distribution without preconceived shape is achieved through a multi-scale (meso and macro) topology optimization method that produces conceptual designs of lightweight, high performance structures (Liu and Tovar, 2013). The multi-scale approach creates structures filled with functionally-grade cellular material that reduce the bulk mass while improving overall performance. The two scales involved in the design of an ultra-lightweight compliant structure are (mesoscale) cellular material and the (macroscale) structure. The concurrent meso-macro scale design is possible through use of the homogenization theory that finds the effective macroscale properties of the mesoscale layout (Torquato, 2010). Given the design volume (design domain), and the mechanical and thermal boundary conditions (load and fixed boundaries), the macroscale structure optimization finds a functionally-graded architecture and layout that maximizes thermo-mechanical performance under functional constraints (e.g. failure, equilibrium conditions). The mesoscale optimization finds the cellular (porous) material topology that achieves the thermo-mechanical targets imposed by the macroscale. Manufacturing constraints include avoiding of closed cells as well as a minimum feature size.

The purpose of using a porous structure is to reduce the weight, save material and manufacturing cost, and enhance thermal performance. Topology optimization also maximizes die performance. This method could be applied for multi-scales. In Section 4, a conceptual model for macroscale is developed to illustrate the generation of thermal-mechanical porous structure.

3 Design for AM

Guiding and ultimately automating design for AM is part of the proposed framework scope and objectives. Adam *et al.* (Adam and Zimmer, 2014) used standard elements to develop basic design rules for AM. Design rules were created for three types of AM processes; Laser Sintering (LS), Laser Melting (LM) and Fused Deposition Modeling (FDM). Few other research works have tackled the issue (Kerbrat *et al.*, 2010, Sambu *et al.*, 2002), (Filippi and Cristofolini, 2007), and (Ponche *et al.*, 2012). On the other hand, AM allows for the design of cooling channels that are conformal to the mold cavity (Filippi and Cristofolini, 2007). A specific design approach for the design of conformal cooling channels for injection molding was proposed (Ponche *et al.*, 2012). Initially, the mold surface is decomposed into sections as different zones. Using these, design parameters like coolant pressure drop, coolant temperature uniformity, sufficient cooling, uniform cooling, mold strength, and deflection are considered in designing the conformal cooling channels.

Our research will develop a comprehensive set of systemic design rules to be integrated with CAD modeling to automate the process of developing viable plastic injection dies with conformal cooling channels. The approach adopts a 3-level formulation of rules, namely, General, Process-specific, and Machine-specific. We are compiling the literature and will then conduct experimental tests to extract the rules for our specific AM process and machine.

4 FEA of a generic injection molding die with conformal cooling channels

Based on additive manufacturing principles, numerical thermal FEA models for conformal cooling can be created. In this section, two separate models are established in order to verify the modeling accuracy and to offer preliminary information for optimizing the materials distribution in the die, respectively. First, a generic CAD model of an injection tooling die with a circular conformal cooling channel is created in order to validate the accuracy of the simulation. A geometry model is created using CREO parametric software® (Fig. 2a). Then a transient thermal analysis is performed on the generic injection molding model using ANSYS 15.0 workbench. The total height, width and length of the mold are 135 mm, 190 mm, and 200 mm respectively. Conformal cooling channels were produced with a helical sweep of an 8 mm diameter circular cross section with a pitch of 20 mm. The designed part is a 150 mm diameter bowl with a 100 mm height, 5 mm thickness, and an additional 190 mm diameter flange. Using fine meshing and medium smoothing on automatic mesh generator, a total of 94,088 elements were created with 155,990 nodes. The core and cavity material was structural steel and the plastic material was chosen to be polypropylene. Density, specific heat and Isotropic thermal conductivity of the plastic are 830 kg/m^3 , $1,900 \text{ J/kg}$, $0.14 \text{ W/m}^2\text{K}$ respectively. Water was introduced into the cooling channels at 25°C both in core and cavity with a convective thermal coefficient of $5352 \text{ W/m}^2\text{K}$. With a flow rate of 4 lit/min , this flow in the cooling channel is considered to be turbulent. The initial temperature of the plastic mold is 168°C . The locations for these boundary conditions are shown in Fig. 2 (b & c). From the results of FEA analysis running for 150 s of cooling time, we can state that the plastic part takes 7.4 s to cool down to its ejection temperature of 87°C . The re-

sults in Fig. 3 compares well with the literature, for example, Khan et al. investigated that a plastic part molded on an injection tooling die with conformal cooling channel can be cooled down at around 5 s (Khan et al., 2014).

After validating the modeling techniques, a simplified axisymmetric 3D model was developed in order to offer preliminary data for the purpose of optimizing materials distribution between the coolants and cavity (4). Notably, this simplified design may not well adaptive for actual injection molding die, it aims to illustrate the coherence between this modeling step and next step, thermal-mechanical topology optimization. Automatic mesh generator creates a total of 62901 elements and 160048 nodes with fine meshing size. The water temperature for the water coolant is defined as a constant, which is 23°C . The initial temperature of the plastic mold is 168°C , and the materials selection for plastic and die are same as which used in last example.

The results show that in this example the plastic part takes 14.6 s to cool down. The results also show that at the moment of 50 s, it arrives the ejection temperature. A steady state temperature for cavity is approached at around 112 s, which is around 45°C . These results can be seen in Fig. 4(right). After approaching the steady state, the temperature of cavity is comparatively difficult to decrease, hence a lower steady state temperature is desired. In next section, the minimum steady state temperature will be considered as criteria by considering its equivalent energy term heat dissipation to determine the optimal materials distribution between coolants and cavity.

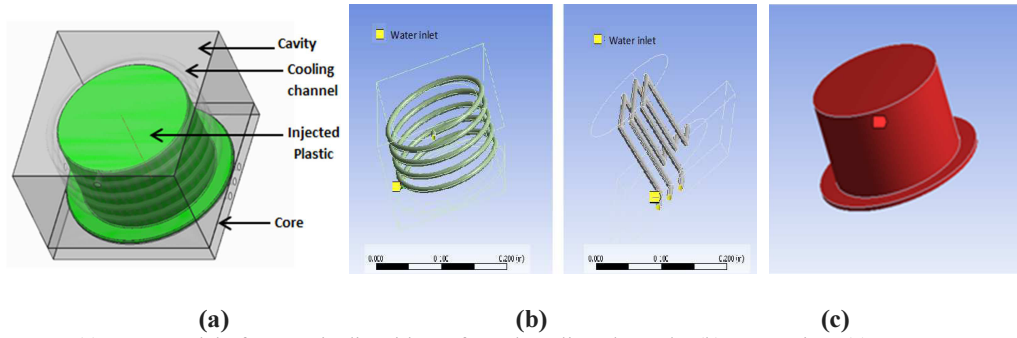


Fig. 2: (a) CAD model of a generic die with conformal cooling channels; (b) convection; (c) part temperature

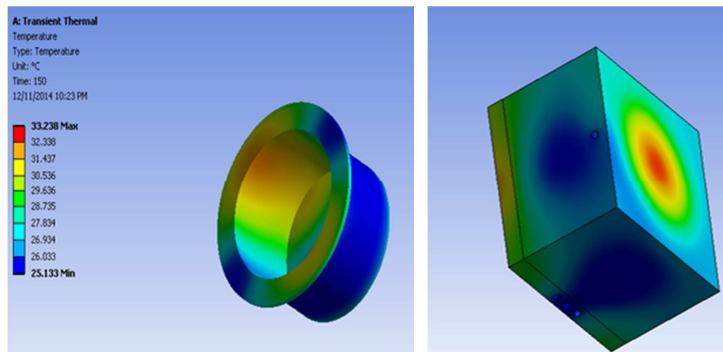


Fig. 3: The temperature distribution after 150 s of transient thermal analysis (left: on the plastic part; right: on the full assembly)

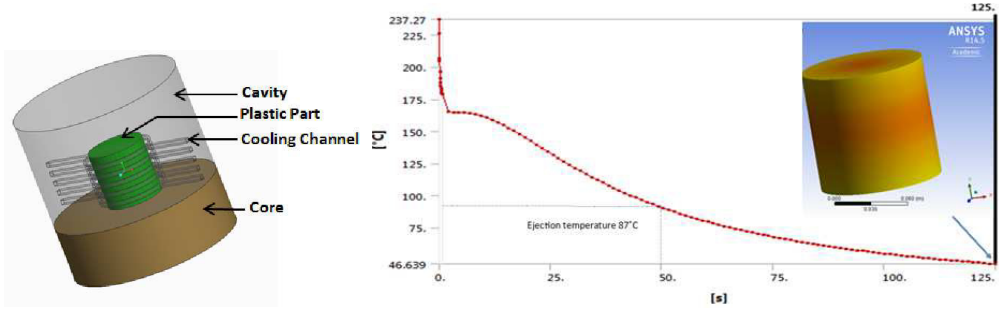


Fig. 4: (Left) The simplified axisymmetric 3D model starting with a 2D section, with conformal cooling channels; (Right) The temperature of the cavity with respect to cooling times.

5 Thermal-mechanical topology optimization

The reduction of die weight can be formulated as a thermal-mechanical topology optimization in order to obtain the optimum material distribution with limit utilization of material ingredient. For this problem, the total objective is defined as a linear combination of two physics objectives,

$$Obj = w_1 Obj_1 + w_2 Obj_2, \quad (1)$$

where the weight factors $w_1 + w_2 = 1$. Here the first objective Obj_1 aims to find the optimal material distribution while there is steady heat conduction in the solid, and the second objective Obj_2 aims to find the optimal material distribution for the structural stability.

To illustrate our methods, a two-dimensional conceptual model for steady state thermal conduction is used as a 2D representation of the simplified model for injection die with conformal cooling. The key parameters for this model are defined based on the results of thermal FEA analysis. The area between the big square with the size of $30 \times 30 \text{ cm}^2$ and the small square with the size of $10 \times 10 \text{ cm}^2$ is made of steel AISI A340. Induced by the imposed heat flux, the temperature for the surface of the inner square is 45°C , and the surface of the outside square is assumed as 23°C . The inner square simulates the cavity, the outside square simulates the coolants, and the area between the two squares simulates the die. If the area between cavity and cooling channel is made of pure solid, this problem can be solved by a finite element analysis, with the layout and the resulting temperature distribution shown in Fig. 5.

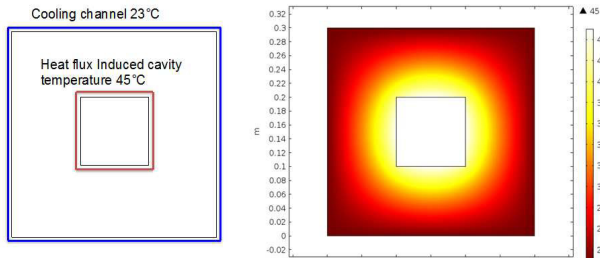


Fig. 5: Steady state thermal conduction model and resulting temperature field

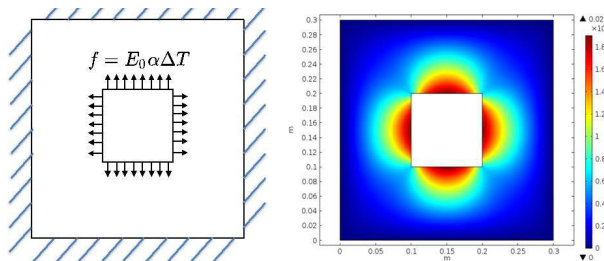


Fig. 6: Mechanical model and resulting displacement field

Meanwhile, the temperature difference between the hot plastic and the cooler cavity may cause the expansion of the mold, which may leads to the deformation of the cavity. In this problem, assuming the thermal expansion stress is applied on the small square's surface from inside to outside, with the outside

boundary of the big square fixed. The magnitude of stress \mathbf{f} is simply calculated as

$$\mathbf{f} = E_0 \alpha \Delta T \quad (2)$$

where E_0 is the Young's modulus of design material, α is coefficient of thermal expansion, and ΔT is temperature difference between hot plastic and cooling channels. The layout of this conceptual model and the resulting displacement field computed by finite element analysis is shown in Fig. 6.

First consider the optimization problem based on steady state thermal conduction. Following the technique described in (Dede, 2012, Sigmund, 2004), A steady state pure heat conduction problem is govern by Fourier's law,

$$-\nabla \cdot (\mathbf{k} \nabla T) = q \quad (3)$$

Particularly, Poisson equation can be derived for our stated problem,

$$\mathbf{k} \cdot \Delta = k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} = q_s \quad (4)$$

where q is the heat flux in general and q_s is the heat flux imposed on the surface of cavity. With this equation, the full optimization problem can be formulated as: Find ρ

$$\text{Minimize: } \int_{\Omega} \mathbf{k}_{ii} (\nabla T)^2 d\Omega \quad (5)$$

$$\text{Subject to: } -\nabla[\mathbf{k}(\rho) \nabla T] = 0; \int_{\Omega} \rho \cdot d\Omega_d - V \leq 0; \mathbf{0} \leq \rho \leq 1$$

where \mathbf{k} is the thermal conductivity tensor, which is a function of dimensionless density ρ in the range from 0 to 1. Here given $\mathbf{k}_{ii}(\rho) = 0.001 + 0.999\rho^p \mathbf{k}_0$, where \mathbf{k}_0 is the thermal conductivity of design material, and $\mathbf{k}_{ij}(\rho) = 0$. p is a penalization number which could relatively enlarge the higher density and shrink the lower density. The method that using this penalization parameter to optimize isotropic material distribution is called SIMP(Solid Isotropic Material with Penalization), which could be seen

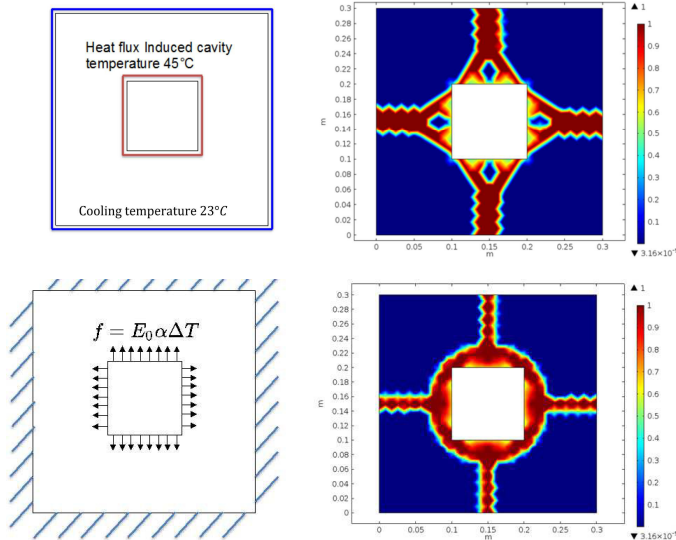


Fig. 7: Optimal materials distribution for thermal physics if at most 20% materials in the design domain are provided: (up) Thermal only; (down) Structural only

material on paths between cavity and cooling channel where the temperature difference is less than other places might be the optimal decision. Comparing Fig. 5 and Fig. 7(up), one can find the optimal materials distribution in general follows the paths with less temperature difference. For example, the materials are distributed on the middle of each edge of the square rather than at the corners.

in (Bendsøe, 1989) for detail. $T(x, y, z)$ is the temperature field in solid, which is a function of location. V is the volume constraint for the optimization. The resulting topology layout using maximum 20% volume of original design domain is shown as Fig. 7(up). The relative density is in the range of 0 to 1.

The result might be understood in an intuitive way. To evaluate for $(\nabla T)^2$ is equivalent to evaluate the magnitude of temperature difference, $\|\nabla T\|$. While $\|\nabla T\|$ is small, it indicates that the heat flux transfers smoothly in the materials. Otherwise, while $\|\nabla T\|$ is high, it

indicates that the heat flux is resisted, i.e. the material might not be efficiently distributed. In another word, distributing the

Next, consider the optimization problem based on mechanical load. This problem can be formulated as a structural stability problem for elastic solid in steady state. The problem can be defined as follows: Find density ρ that minimize the internal strain energy subject to Hooke's law and volume constraint (Sigmund, 2001, Sigmund, 2004):

$$\begin{aligned} & \text{Find } \rho \\ & \text{Minimize } \int_{\Omega} W_s d\Omega \end{aligned} \quad (6)$$

$$\text{Subject to: } \mathbf{F} = \mathbf{K}(E(\rho))\mathbf{u}; \int_{\Omega} \rho \cdot d\Omega_d - V \leq 0; \mathbf{0} \leq \rho \leq \mathbf{1}$$

where \mathbf{K} is the stiffness element matrix, which is a function of Young's Modulus $E(\rho) = \rho^p \cdot E_0$, E_0 is

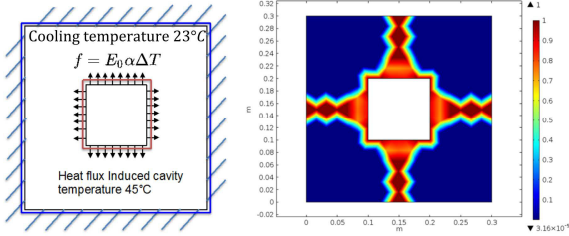


Fig. 8: Optimal materials distribution for mechanical physics if at most 20% materials in the design domain are provided: Combined (Thermal & Structural)

the Young's modulus of design material. \mathbf{u} is the displacement field $\mathbf{u}(x, y, z)$, and strain energy W_s is a function of \mathbf{u}^2 . In another word, minimizing strain energy is equivalent to minimize the displacement magnitude $\|\mathbf{u}\|$ where load is applied. The resulting topology layout of this optimization formulation is shown in Fig. . The relative density is in the range of 0 to 1 as well.

From the resulting topology one may find that the limited materials are priority distributed around the cavity to enhance stiffness and to limit the displacement.

Finally for the thermo-mechanical problem, the goal is to take the sum of weighted thermal and mechanical optimization criteria with limited materials utilization:

$$\begin{aligned} & \text{Find } \rho \\ & \text{Minimize} \\ & w_1 \int_{\Omega} \mathbf{k}_{ii} (\nabla T)^2 d\Omega + \quad (7) \\ & w_2 \int_{\Omega} W_s(\rho) d\Omega \\ & \text{Subject to:} \\ & -\nabla[\mathbf{k}(\rho)\nabla T] = q_s; \\ & \mathbf{F} = \mathbf{K}(E(\rho))\mathbf{u}; \\ & \int_{\Omega} \rho \cdot d\Omega_d - V \leq 0; \\ & \mathbf{0} \leq \rho \leq \mathbf{1} \end{aligned}$$

Fig.8 shows the density distribution based on total objective function. For this specific case, we assume the volume fraction is 20% and $w_1 = w_2 = 0.5$. The resulting layout shows that, the material distribution simultaneously responds to transfer heat in comparatively efficient paths and increases the stiffness close to cavity to reduce the displacement.

Our results show the reduction of mass can increase the heat dissipation and strain energy stored in the component, therefore decreasing its performance. However, the reduction of

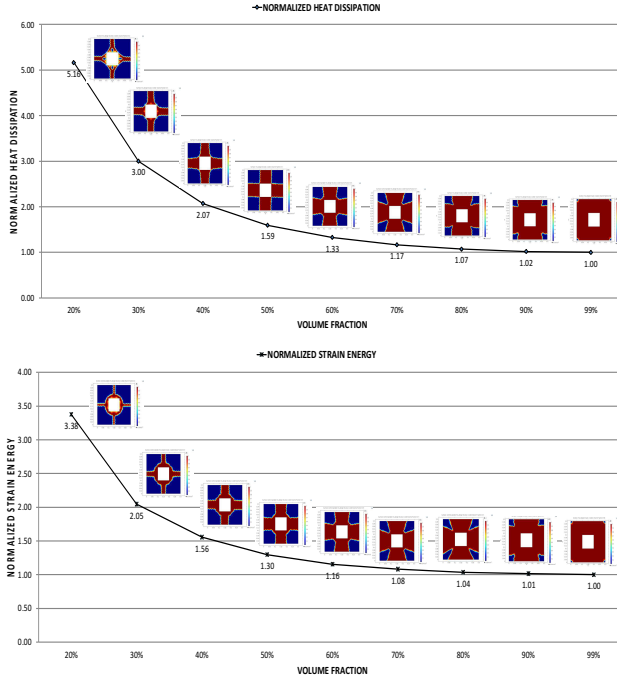


Fig. 9: (up) The variation of volume fraction causes the change of normalized heat dissipation; (down) The variation of volume fraction causes the change of normalized strain energy

mass will save the material and manufacturing cost as well. Consequently, the optimal mass reduction may be adopted when the cost-saving and performance compromising levels are balanced. For the thermal topology optimization in Fig. 9(up) it shows that, suppose the normalized heat dissipation is 1 while 99% materials are contained in the design domain, the normalized heat dissipation will increase respect to the reducing of materials volume fraction. Similarly, for the mechanical thermal optimization, it indicates the analogous trend, shown in Fig. 9(down). However, it is noticed that these trends are not linear, i.e. the sensitivity of volume reduction does not remain constant. For our conceptual model, while the volume fraction is larger or equal than 40%, the heat dissipation and strain energy increasing rates are small with respect to the reduction of volume, compared to the volume fraction less than 40%. This implies for our conceptual model, a volume reduction in the range of 50% to 60% may be applicable, since such reduction doesn't obviously affect the component's performance. Besides using normalized indicators, an alternative approach is to using max cavity temperature to evaluate the thermal performance and directly using strain energy (without normalization) to evaluate the mechanical performance, with respect to different volume fractions.

In Fig. 10, the picture on the left shows that the cavity temperature is increased with respect to the decrease of volume fraction, which implies if the coolant temperature and the heat flux are fixed, the cooling rate would be decreased due to the reduction of volume fraction. While the picture on the right indicates, if the temperature difference between cavity and coolant is fixed, the reduction of volume fraction would increase the deformation and leads to increase strain energy stored in the component. This similar trend is also satisfied in thermal-mechanical optimization. Furthermore, our result illustrates, for thermal-mechanical optimization, the material distribution aims to achieve the weighted normalized total energy. In other words, the materials distribution is affected by the volume fraction as well as the weight factor imposed on thermal and mechanical objectives. For example in Table 1, one can see while the volume fraction is 30% and the heat dissipation is less weighted ($w_1/w_2: 0.2/0.8$), the mechanical criteria dominate the optimization problem and more materials are distributed surrounding the cavity to enhance the stiffness and decrease the deformation, or vice versa. Indeed, the difference can be quantified, as shown in Table 2.

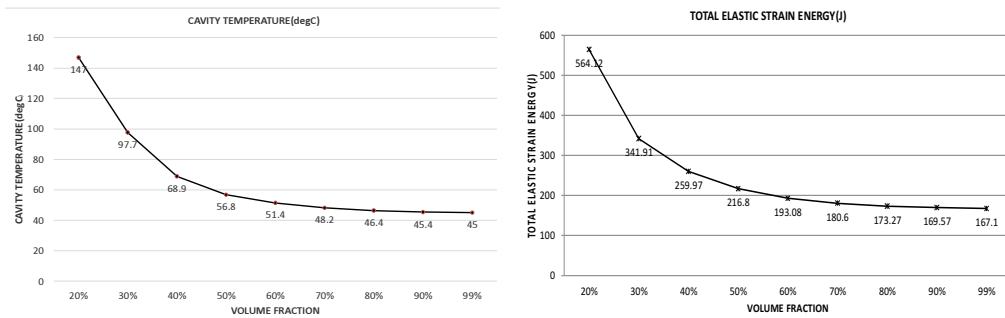
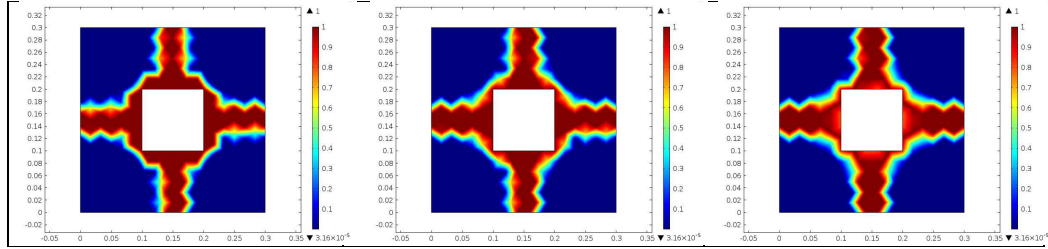


Fig. 10: Left: The max cavity temperature changes with respect to volume fraction changes. Right: The total elastic strain energy changes with respect to volume fraction changes.

6. Material characterization

Table 1 Materials distribution for thermal-mechanical optimization with respect to 30% volume fraction and different weight factor for each objective (w_1 is the weight factor imposed on heat dissipation while w_2 is the weight factor imposed on strain energy). From left to right: $w_1/w_2 = 0.2/0.8$, $w_1/w_2 = 0.5/0.5$, $w_1/w_2 = 0.8/0.2$ respectively.



The goal of experimental part is to validate the designs from modeling and optimization work, which is the material testing part in Fig. 1. In this paper, we have planned to systematically characterize the microstructure of 3D printed parts printed by using EOS Laser Sintering System (EOSINT M280 EOS GmbH electro Optimal System, Germany). Due the early stage of the project, we only give a preliminary microstructure analysis in this work.

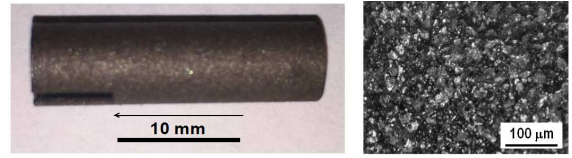


Fig. 11: Left: 3D printed metal pin (arrow shows the build direction); Right: the surface microstructure of the printed part

In a 3D printing process such as LDMD, a high-powered optic laser selectively fuses metal powder so the part is vertically built in transverse layers. Since the layers do not bond as well in the vertical direction as they do along the transverse plane, the part is prone to laminate weakness. Unfortunately, in literature there are virtually no confirmed mechanical properties of the 3D printed parts to compare with their machined parts counterparts. Therefore, a comparative study is planned through tensile, compressive, and fatigue tests. In addition, microstructure and composition of the parts is examined using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Statistical methods are planned to establish the correlation between the microstructure and mechanical property and the results will be numerically incorporated to support the optimal design.

A sample of 3D printed metal part is shown in Fig. 11(left). It was fabricated using a Direct Laser Metal Sintering (DLMS) system. The material was MaragingSteel MS1, which is a Martensite-hardenable steel. Its chemical composition corresponds to US classification 18% Ni Maraging 300, European 1.2709 and German X3NiCoMoTi 18-9-5. The literature of studying the difference between the materials processed using DLMS or similar techniques and conventional approach is scarce. There are only a few comparative studies on (Cronskär et al., 2013) and stainless steel (Gratton, 2012). There is still a need for a thorough investigation of the materials properties produced by DLMS technique.

The surface of the 3D printed sample was observed using optical microscopy, as shown in Fig. 11(right). The powder particle structures are evident with an average particle diameter approximately $8 \mu m$. The microstructure does not show a strong crystallographic orientation.

Table 2 Max cavity temperature and stored strain energy with respect to different volume fraction(VF) and weight factor for each objective

VF=30%			VF=40%		VF=50%	
w_1/w_2	Max cavity temperature (°C)	Stored strain energy(J)	Max cavity temperature (°C)	Stored strain energy(J)	Max cavity temperature (°C)	Stored strain energy(J)
0.5/0.5	100	367.99	69.9	258.9	58.6	214.25
0.8/0.2	99.6	410.8	69.9	259.41	58.2	215.03
0.2/0.8	102	349.2	70.9	257.23	58.7	211.63

7. Conclusion & Future Work

In this paper, a framework for optimizing additive manufacturing of plastic injection molds was proposed. To start with, numerical thermal FEA modeling, thermal-mechanical topology optimization in macroscale, and material characterization are investigated. Advanced numerical simulation is implemented for a typical die with conformal cooling channels to predict cycle time, part quality and tooling life on ANSYS benchmark. Then, a 2D thermo-mechanical topology optimization algorithm is being developed based on the results of the numerical model to minimize the die weight and enhance its thermal performance. Stress and temperature distributions as well as optimal material density distribution were presented. Furthermore, the relationship between material cost constraints and components performance, and the alternative between optimizing thermal performance and mechanical performance is discussed. Our key finding quantifies that the materials between cavity and coolants may have potential to be efficiently reduced without decreasing the performance of the components much. Finally, material characterization was started using a 3D printed metal pin, for which microstructure was observed. In future, the above simulations will be extended and integrated for a more realistic representation of the injection molding process using optimal 3D printed dies with conformal cooling. For example, the die simulation will be extended to include coupled thermal-structural analysis. In fact, the plan is to analyze the flow in the channels and its effect on the die and part, as well as the volumetric shrinkage of the die and part after freezing, cooling time and total cycle time with conformal channels, temperature distribution after the part being ejected under saving of the material costs of the die. On the other hand, the 2D model for topology optimization will be extended to 3D. Also, dies with conformal cooling will be designed based on designed rules for AM. Finally, experiments and MD simulation will be conducted to predict material properties and mechanical behavior of 3D printed dies. Plus, in our work, simulation software packages to be utilized include ANSYS, COMSOL, Autodesk Moldflow Advisor and MATLAB. We are looking into more software packages including Moldex3D for their capabilities and feasibility for our research.

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